

# Thermal conductivity and water vapour transmission properties of wood-based materials

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**Abstract** For several wood-based materials (plywood, OSB, melamine faced board (MFB), particle board and fibre board), the thermal conductivity was determined as a function of the temperature (ranging between 10 and 30 °C) and also the moisture content (from an oven-dry sample up to a moisture content at 80% RH). Furthermore, the water vapour resistance factor of these materials as well as of the coating (at MFB) and the diffusion coefficient were determined under dry cup (performance at low humidity dominated by vapour diffusion) and wet cup (performance at high humidity with liquid water and vapour transport) conditions.

Thermal conductivity increases with rising temperature, moisture content and density. Moreover, a clear decrease of thermal conductivity was found with decreasing particle size at the same density level, from solid wood over plywood and particle board to fibre board. The water vapour resistance factor of the wood-based materials increases with rising density and decreases with increasing moisture content. An influence of the particle and fibre board thickness was also revealed. In contrast to the remaining materials, an increase of the water vapour resistance factor with increasing moisture content was measured for the coating. The diffusion coefficient decreases with rising density and moisture content.

## Wärmeleitfähigkeit und Wasserdampfdiffusion von Holzwerkstoffen

**Zusammenfassung** An verschiedenen Holzwerkstoffen (Buchensperrholz, OSB, melaminbeschichtete Platten

(MFB), Span- und Faserplatten) wurde die Wärmeleitfähigkeit in Abhängigkeit von der Temperatur (Temperaturbereich zwischen 10 und 30 °C) und von der Feuchte (darrtrocken bis Ausgleichsfeuchte bei 80% relativer Luftfeuchte) bestimmt. Weiter wurden die Wasserdampfdiffusionswiderstandszahlen sowohl der Holzwerkstoffe als auch der Beschichtungen (bei MFB) und die Diffusionskoeffizienten im Trocken- (Dampfdiffusion vorherrschend) und Feuchtbereich (Flüssigwasser- und Dampftransport maßgebend) ermittelt.

Die Wärmeleitfähigkeit nimmt mit zunehmender Temperatur, Feuchte und Dichte zu. Es konnte weiter bei gleicher Dichte eine deutliche Erniedrigung der Wärmeleitfähigkeit mit zunehmendem Aufschlussgrad der Holzwerkstoffe von Vollholz über Sperrholz und Spanwerkstoffe bis zu den Faserwerkstoffen festgestellt werden. Die Wasserdampfdiffusionswiderstandszahlen der untersuchten Holzwerkstoffe nehmen mit zunehmender Dichte sowie mit abnehmendem Feuchtegehalt zu. Auch hat die Plattendicke von Span- und Faserplatten einen Einfluss auf die Wasserdampfdiffusionswiderstandszahl. Bei den Beschichtungen nimmt die Wasserdampfdiffusionswiderstandszahl im Gegensatz zu den übrigen Materialien mit zunehmender Feuchte zu. Der Diffusionskoeffizient nimmt mit zunehmender Dichte und Feuchte ab.

## Introduction

Data for the thermal conductivity and the water vapour resistance factor of modern wood-based materials are often lacking or are incomplete. The properties of current products are thus often extrapolated from established values of well-known materials. This especially applies to values that depend on the moisture content and temperature. In this present study, the thermal conductivity depending on the temperature and on the moisture content as well as

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the water vapour resistance factor under dry cup and wet cup conditions, were evaluated for several wood-based materials such as plywood, OSB, particle board, and fibre board.

Amongst other factors, thermal conductivity also depends on density, moisture content, temperature, direction of heat flow and particle size (Suleiman et al. 1999, Bader et al. 2007). For solid wood parallel and perpendicular to the grain, Kollmann (1951) already defined equations for the thermal conductivity (at 27 °C and 12% moisture content) depending on density as follows (converted into SI notation by Niemz 1993):

- Parallel to the grain:

$$\lambda_{\parallel} = 0.026 + 0.46 \cdot \rho \cdot 10^{-3} \quad (1)$$

- Perpendicular to the grain:

$$\lambda_{\perp} = 0.026 + 0.195 \cdot \rho \cdot 10^{-3} \quad (2)$$

where  $\lambda_{\parallel}$  is the thermal conductivity parallel to the grain [W/(m K)],  $\lambda_{\perp}$  the thermal conductivity perpendicular to the grain [W/(m K)], and  $\rho$  the density [kg/m<sup>3</sup>].

For particle board, Schneider and Engelhardt (1977) determined the influence of density on thermal conductivity. From a thermal conductivity-density diagram, the following equations for the thermal conductivity of dry particle boards perpendicular to the board plane at 10 °C can be derived:

$$\lambda_{\text{pb(u)}} = 0.016 + 0.144 \cdot 10^{-3} \cdot \rho \quad (3)$$

$$\lambda_{\text{pb(p)}} = 0.026 + 0.140 \cdot 10^{-3} \cdot \rho \quad (4)$$

where  $\lambda_{\text{pb(u)}}$ ,  $\lambda_{\text{pb(p)}}$  are the thermal conductivity of particle board with urea (u) or phenolic (p) resin [W/(m K)], and  $\rho$  is the density [kg/m<sup>3</sup>].

The in-plane conductivity was 1.9–2.4 times higher than the thermal conductivity perpendicular to the board plane.

The influence of moisture on the thermal conductivity was discussed by Cammerer and Achtziger (1984) for several wood species and particle board. They found the thermal conductivity to increase by 1–2%, per percent increase of moisture content for solid wood and 1–2.4% for particle boards.

Values for the water vapour resistance of several wood-based materials have only been industrially calculated. Radovic et al. (2001) give an overview of the water vapour resistance factor and the thermal conductivity of many industrially produced wood-based materials. The values, however, do not consider the influence of density, temperature and moisture.

## Materials and methods

Thirtytwo industrially fabricated wood-based materials with following thicknesses were investigated:

- Plywood (beech): 25, 35, 50 mm,
- OSB 3: 12, 15, 18, 22, 25 mm,
- Particle boards:
  - Particle board (V20): 6, 10, 16, 19, 25, 40 mm,
  - Melamine faced boards (with a particle board substrate): 16, 25, 40 mm,
  - Laminate flooring (with a particle board substrate): 7\* mm.
- Fibre boards:
  - MDF (V20): 3, 6, 10, 16, 19, 25, 40 mm,
  - Melamine faced boards (with a MDF substrate): 19, 25 mm,
  - Laminate flooring (with a HDF substrate): 7\*, 8 mm,
  - MDF wall panel (glued with PMDI): 15 mm.

Explanations: OSB 3 = oriented strand boards for supporting purposes in moist surroundings, here: glued with PMDI (polymeric methylene diphenyl diisocyanates) and MUPF (melamine urea phenol formaldehyde); V20 = Usage in rooms with generally low humidity (particle boards and MDF glued with UF (urea formaldehyde)); MDF = medium density fibreboard; HDF = high density fibreboard; \* = the whole plate as well as the substrate only was tested.

To determine the thermal conductivity, three to five specimens per type sized 500 mm × 500 mm × sample thickness were analysed. Prior to testing, the boards were conditioned at standard climatic conditions (20 °C and 65% RH). The measurements were carried out with the guarded hot plate apparatus  $\lambda$ -Meter EP500 (Lambda-Messtechnik GmbH, Dresden) according to ISO 8302 at 10, 20, and 30 °C. With a linear regression through the values at the three temperatures, the thermal conductivity at 10 °C ( $\lambda_{10, \text{reg}(T)}$ ) and the change of the thermal conductivity with increasing temperature ( $\Delta\lambda_{T^{\circ}\text{C}}$  = slope of the regression) were determined. To reveal the influence of the moisture content, several board types were selected (plywood: 25 mm, OSB: 18 mm, particle board: 16 mm, MDF: 3 and 16 mm, substrate of laminate flooring (HDF): 7 mm). Therefore, five specimens per type were conditioned at 20 °C and 40, 65, and 80% RH and also dried and tested for all conditions at three temperatures (10, 20, 30 °C). First, the thermal conductivity at 10 °C was determined for all conditions as described above using a linear regression through the values of the three temperatures and then a further linear regression was placed through the values at different moisture contents. Hence the values under dry condition ( $\lambda_{10, \text{dry, reg}(\omega)}$ ) as well as the change of the thermal conductivity with increasing moisture content ( $\Delta\lambda_{\omega}$ ) were determined at a temperature of 10 °C.

For measuring the water vapour diffusion, three cylindrical specimens of 140 mm diameter  $\times$  sample thickness were used per climate and type. The tests were carried out according to ISO 12572 under dry cup (20 °C–0/65% RH) and wet cup conditions (20 °C–100/65% RH). The specimens were first conditioned at standard climatic conditions (20 °C/65% RH) and then put on top of a glass vessel filled up to approximately 20 mm under the brim with either totally desalinated water or a desiccant (silicagel). The specimens were laterally sealed with a close-fitting endless rubber band. After attaining the equilibrium moisture content, the vessels with the specimens were weighed seven times with an interval of 1 to 4 days between each weighing depending on the thickness and the permeability of the respective specimen. Due to the change of mass, which corresponds to the water vapour flow rate through the specimens ( $G$ ), the water vapour resistance factor was calculated by the following equation (cf. ISO 12572, Annex G):

$$\mu = \frac{\delta_a}{\delta_p} = \frac{\delta_a}{W_{pc} \cdot d} = \frac{\delta_a}{d} \cdot \left( \frac{A \cdot \Delta p_v}{G} - \frac{d_a}{\delta_a} \right) \quad (5)$$

- $\mu$  Water vapour resistance factor [–]
- $\delta_a$  Water vapour permeability of air with respect to the partial vapour pressure [kg/(m s Pa)]
- $\delta_p$  Water vapour permeability with respect to the partial vapour pressure [kg/(m s Pa)]
- $W_{pc}$  Water vapour permeability with respect to the partial vapour pressure corrected by the air layer between the base of the specimen and the desiccant or the desalinated water in the test cup [kg/(m<sup>2</sup> s Pa)]
- $d$  Mean thickness of the specimen [m]
- $A$  Area of the specimen [m<sup>2</sup>]
- $\Delta p_v$  Water vapour pressure difference across the specimen [Pa]
- $G$  Water vapour flow rate through the specimen [kg/s]
- $d_a$  Thickness of the air layer in the test cup between the base of the specimen and the desiccant or the desalinated water [m].

Then the diffusion coefficient could be determined as follows (according to Siau 1995):

$$D = \frac{\delta_p \cdot p_o \cdot V}{w_o} \cdot \frac{\partial H}{\partial M} \quad (6)$$

- $D$  Diffusion coefficient [m<sup>2</sup>/s]
- $\delta_p$  Water vapour permeability with respect to the partial vapour pressure [kg/(m s Pa)]
- $p_o$  Saturated water vapour pressure [Pa]
- $V$  Volume of the specimen at standard climatic conditions [m<sup>3</sup>]
- $w_o$  Owendry mass of the specimen [kg]
- $\partial H$  Difference of relative humidity [%]
- $\partial M$  Difference of moisture content [%].

For Eq. 6, a moisture content of 25% was assumed for all wood-based materials at 100% relative humidity. This is 0.4–2.4% higher than the values of comparable wood-based materials measured by Sonderegger and Niemz (2006) at 95% relative humidity.

To calculate the water vapour resistance factor of the double-sided melamine faces of the coated specimens, the following equation was used (depending on Cammerer 1956) neglecting the water vapour transfer coefficients:

$$\mu_{mf} = \frac{s_{dc} - s_{duc}}{d_{mf}} \quad (7)$$

- $\mu_{mf}$  Water vapour resistance factor of the melamine face [–]
- $s_d$  Water vapour diffusion-equivalent air layer thickness of the coated (c) or uncoated (uc) specimen [m]
- $d_{mf}$  Total thickness of the two melamine faces of a specimen [m].

Each coating was 0.1 mm thick except for laminate flooring with a HDF substrate (here: one coating was 0.2 mm thick because of an additional overlay). The reverse side of each laminate flooring was not melamine- but phenolic-faced.

## Results and discussion

Table 1 shows the thermal conductivity of all wood-based materials tested after being conditioned at 20 °C and 65% RH. The beech plywood had the highest values (0.158–0.173 W/(m K)) followed by HDF (0.124–0.137 W/(m K)), MDF (0.108–0.123 W/(m K)), particle board (0.099–0.118 W/(m K)) and OSB (0.098–0.106 W/(m K)). MDF wall panel, which had by far the lowest density of the tested materials, had the smallest value (0.076 W/(m K)). The coated HDF, MDF and particle boards had higher values than the uncoated boards. This is mainly influenced by the higher density of the coated boards. Figure 1 shows the thermal conductivity of all materials depending on the density. For fibre and particle boards, the linear regression is plotted into the figure. Furthermore, the values of Eq. 2 (solid wood perpendicular to the grain by Kollmann (1951)) and Eqs. 3 and 4 (particle board with urea and phenolic resin respectively by Schneider and Engelhardt (1977)) are plotted in this figure. A clear decrease of the thermal conductivity with decreasing particle size from solid wood over plywood and particle board to fibre board was found. For fibre boards, the slope of the plotted regression corresponds to the values of Schneider and Engelhardt (1977) measured on both types of particle boards, even though on a lower level. In contrast, the slope of the particle boards measured within this project is considerably lower. This probably depends on the different particle sizes.

**Table 1** Thermal conductivity ( $\lambda_{10,reg(T)}$ ) with temperature correction factor ( $\Delta\lambda_{T^{\circ}C}$ ). MC = moisture content; COV = coefficient of variation  
**Tabelle 1** Wärmeleitfähigkeit ( $\lambda_{10,reg(T)}$ ) mit Temperatur-Korrekturfaktor ( $\Delta\lambda_{T^{\circ}C}$ ). MC = Feuchtegehalt; COV = Variationskoeffizient

Material	Thickness		No.	Density	MC	$\lambda_{10,reg(T)}$	COV	$\Delta\lambda_{T^{\circ}C}$	COV	$\Delta\lambda_{T^{\circ}C}$
	Required [mm]	Measured [mm]								
Plywood (beech)	25	26.2	5	747	10.5	0.1581	2.0	0.00061	6.3	0.38
	35	35.7	5	777	10.3	0.1728	2.6	0.00059	4.7	0.34
	50	50.4	5	748	10.7	0.1678	0.7	0.00053	2.2	0.32
OSB 3	12	11.9	5	662	9.5	0.0984	5.7	0.00029	8.7	0.30
	15	15.2	5	638	9.6	0.1056	3.3	0.00033	12.6	0.31
	18	18.2	5	617	9.9	0.1028	2.3	0.00041	11.5	0.40
	22	22.0	5	626	9.6	0.1058	3.6	0.00030	11.2	0.28
	25	25.5	5	618	9.6	0.1054	6.0	0.00030	5.2	0.29
Particle board (V20)	6	6.0	5	762	9.6	0.1141	0.9	0.00036	0.3	0.31
	10	10.4	5	710	9.0	0.1117	2.4	0.00035	9.7	0.31
	16	16.6	5	648	9.7	0.1103	1.8	0.00034	15.0	0.31
	19	18.9	5	637	8.8	0.0991	1.1	0.00045	5.6	0.45
	25	25.4	5	621	9.4	0.1074	0.8	0.00035	7.6	0.33
	40	38.5	5	624	8.3	0.1088	1.4	0.00036	5.0	0.33
Melamine faced board (particle board)	16	15.9	5	689	9.3	0.1134	2.6	0.00040	16.3	0.35
	25	25.4	5	637	9.3	0.1084	1.9	0.00033	6.3	0.31
	40	38.9	5	637	9.2	0.1143	1.6	0.00041	5.7	0.36
Substrate of laminate flooring (particle board)	7	6.9	5	779	10.1	0.1110	1.0	0.00037	7.7	0.33
Laminate flooring (particle board)	7	7.0	5	821	9.8	0.1182	0.3	0.00035	3.8	0.30
MDF (V20)	3	3.0	5	830	6.8	0.1197	—	0.00044	0.0	0.37
	6	6.1	5	840	7.6	0.1210	0.9	0.00032	8.8	0.27
	10	10.1	5	798	8.5	0.1198	0.7	0.00034	3.5	0.28
	16	16.4	5	744	7.7	0.1069	0.4	0.00031	5.2	0.29
	19	18.9	5	808	7.7	0.1183	1.0	0.00042	6.6	0.36
	25	25.1	3	741	8.5	0.1077	0.9	0.00031	5.5	0.29
	40	40.3	5	763	6.9	0.1228	0.8	0.00034	9.6	0.28
Melamine faced board (MDF)	16	16.3	5	766	8.3	0.1123	1.1	0.00026	19.3	0.23
	25	24.6	4	769	8.5	0.1105	0.9	0.00037	4.5	0.33
Substrate of laminate flooring (HDF)	7	6.4	5	877	7.7	0.1241	1.8	0.00043	4.6	0.35
Laminate flooring (HDF)	7	6.6	5	912	8.1	0.1290	0.6	0.00033	6.4	0.26
	8	7.8	5	925	8.2	0.1371	2.1	0.00046	8.7	0.33
MDF wall panel	15	15.1	5	529	8.8	0.0761	1.0	0.00037	2.7	0.49

Flooring boards with a high density have exclusively small particles and thereby similar values like fibre boards. The other particle boards with lower density are three-layered with larger particles in the middle layer and agree well with the values of Schneider and Engelhardt (1977) for particle boards with urea resin.

To measure the influence of the board thickness, all values for thermal conductivity were adjusted to a mean density of the respective material depending on the slopes in Fig. 1 (for OSB, the same gradient as for particle board was used; for plywood, the gradient of the formula of Kollmann (1951) was used). Figure 2 shows the corrected values depending on the board thickness. No clear correlation between these two properties could be found.

Table 2 shows the thermal conductivity depending on the moisture content. As expected, the values at dry conditions are lower than the values at standard climatic conditions, but the ranking between the materials is the same. Plywood shows the highest change of thermal conductivity with increasing moisture content (both absolutely and relatively) and OSB the lowest, while particle and fibre boards have medium values.

The characteristics of water vapour flux through the investigated materials are shown in Table 3 in terms of the water vapour resistance factor and the diffusion coefficient under dry and wet conditions. The coefficients of variation for the values of the uncoated fibre and particle boards are predominantly low. For OSB, plywood and the coated

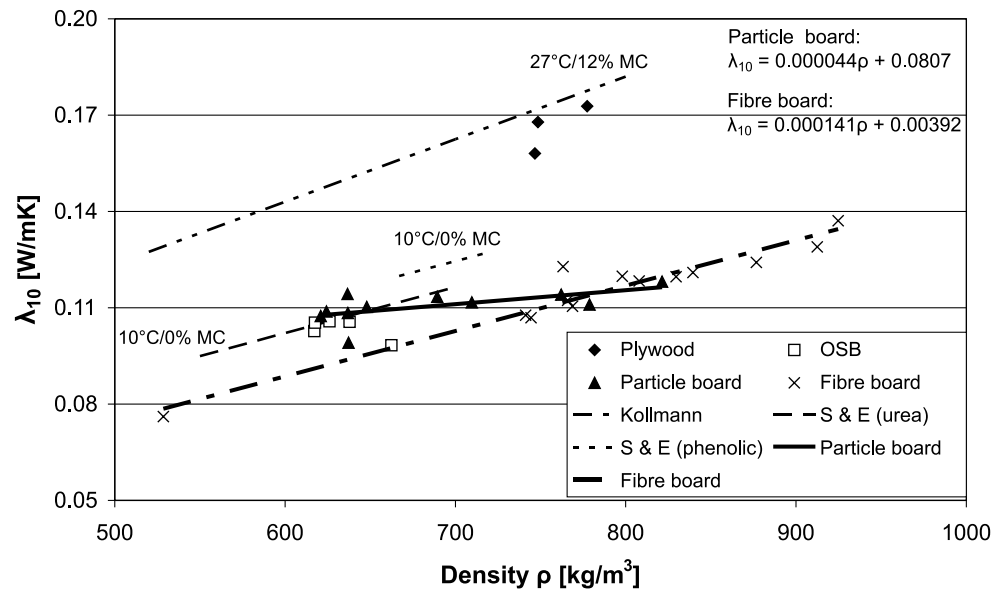
**Table 2** Thermal conductivity ( $\lambda$ ) depending on the moisture content. Mean values of 5 specimens per type (at dry condition only 3 specimens per type);  $\lambda_{10,\text{dry},\text{reg}(\omega)} = \lambda$  at dry condition and 10 °C;  $\Delta\lambda_\omega$  = change of  $\lambda$  per percent moisture content in W/(m K) and in percent; COV = coefficient of variation

**Tabelle 2** Wärmeleitfähigkeit ( $\lambda$ ) in Abhängigkeit vom Feuchtegehalt. Mittelwerte von 5 Proben pro Variante (im darrtrockenen Zustand nur 3 Proben);  $\lambda_{10,\text{dry},\text{reg}(\omega)} = \lambda$  von darrtrockenen Platten bei 10 °C;  $\Delta\lambda_\omega$  = Änderung von  $\lambda$  pro Prozent Feuchteänderung in W/(m K) und in Prozent; COV = Variationskoeffizient

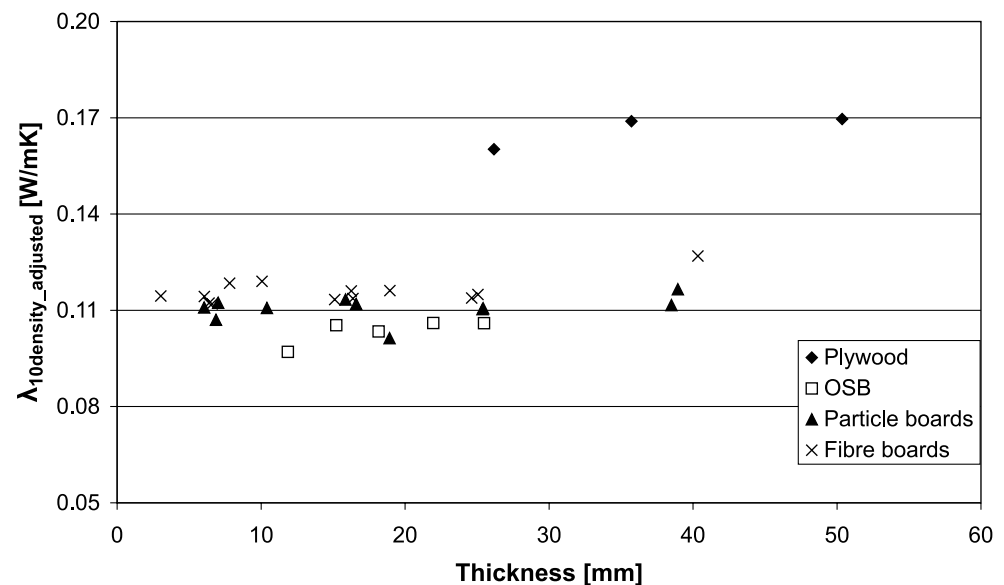
Material	Thickness <sup>1)</sup> [mm]	Density <sup>1)</sup> [kg/m <sup>3</sup> ]	$\lambda_{10,\text{dry},\text{reg}(\omega)}$ [W/(m K)]	COV [%]	$\Delta\lambda_\omega$ [W/(m K %)]	COV [%]	$\Delta\lambda_\omega$ [%/%]
Plywood (beech), 25 mm	25.7	679	0.1304	1.27	0.00255	6.9	1.96
OSB 3, 18 mm	18.4	562	0.0959	1.94	0.00074	28.5	0.77
Particle board (V20), 16 mm	16.4	597	0.0965	2.37	0.00128	21.2	1.32
MDF (V20), 3 mm	2.9	802	0.1104	1.68	0.00115	24.3	1.04
MDF (V20), 16 mm	16.2	696	0.0974	1.35	0.00121	14.1	1.24
Substrate of laminate flooring (HDF), 7 mm	6.6	785	0.1138	1.14	0.00151	11.7	1.32

<sup>1)</sup> At dry condition

**Fig. 1** Thermal conductivity depending on the density (mean values) with linear regressions for particle and fibre boards (own measurements and literature data).  $\lambda_{10}$  = Thermal conductivity at 10 °C/65% RH  
**Abb. 1** Wärmeleitfähigkeit in Abhängigkeit von der Dichte (Mittelwerte) mit Ausgleichsgeraden für Span- und Faserplatten (eigene Messungen und Literaturwerte).  $\lambda_{10}$  = Wärmeleitfähigkeit bei 10 °C/65% relativer Luftfeuchte



**Fig. 2** Thermal conductivity (density adjusted) depending on board thickness (mean values)  
**Abb. 2** Wärmeleitfähigkeit (dichtekorrigiert) in Abhängigkeit von der Plattendicke (Mittelwerte)



**Table 3** Water vapour resistance factors ( $\mu$ ) and diffusion coefficients ( $D$ ) derived from dry and wet cup tests. Mean values of 3 specimens per type (for thickness and density, mean values of dry and wet cup tests were calculated). MC = moisture content; COV = coefficient of variation  
**Tabelle 3** Wasserdampfdiffusionswiderstandszahlen ( $\mu$ ) und Diffusionskoeffizienten ( $D$ ) bestimmt im trockenen und feuchten Bereich. Mittelwerte aus 3 Proben pro Variante (Dicke und Dichte wurden aus den Mittelwerten beider Messbereiche gebildet). MC = Feuchtegehalt; COV = Variationskoeffizient

Material	Thickness		Density	Dry cup					Wet cup				
	Required [mm]	Measured [mm]		MC [%]	$\mu_{\text{dry}}$ [–]	COV [%]	$\mu_{\text{mf,dry}}$ [–]	$D_{\text{dry}}$ [m <sup>2</sup> /s]	MC [%]	$\mu_{\text{wet}}$ [–]	COV [%]	$\mu_{\text{mf,wet}}$ [–]	$D_{\text{wet}}$ [m <sup>2</sup> /s]
Plywood (beech)	25	26.0	738	7.06	97.8	18.4		$5.16 \times 10^{-11}$	15.95	44.1	23.2		$3.92 \times 10^{-11}$
	35	35.4	778	8.15	100.8	18.8		$4.38 \times 10^{-11}$	14.95	66.0	19.9		$2.62 \times 10^{-11}$
	50	50.1	756	9.50	97.2	4.4		$4.22 \times 10^{-11}$	15.01	48.8	15.2		$3.82 \times 10^{-11}$
OSB 3	12	11.9	659	7.11	100.5	4.2		$5.59 \times 10^{-11}$	18.02	42.8	14.8		$4.46 \times 10^{-11}$
	15	15.0	638	6.98	116.8	0.1		$4.97 \times 10^{-11}$	18.28	47.3	20.3		$4.24 \times 10^{-11}$
	18	18.3	618	7.53	112.6	16.6		$5.06 \times 10^{-11}$	18.15	47.6	5.7		$4.54 \times 10^{-11}$
	22	22.0	644	7.18	98.8	17.7		$5.97 \times 10^{-11}$	16.70	75.3	7.2		$2.54 \times 10^{-11}$
	25	25.6	629	7.25	139.1	16.4		$4.34 \times 10^{-11}$	15.91	93.3	26.3		$2.20 \times 10^{-11}$
Particle board (V20)	6	5.9	776	7.59	65.1	7.8		$7.39 \times 10^{-11}$	16.50	27.1	4.2		$5.81 \times 10^{-11}$
	10	10.3	710	8.15	56.9	8.6		$8.29 \times 10^{-11}$	15.09	25.1	15.5		$7.58 \times 10^{-11}$
	16	16.4	654	7.45	29.7	3.2		$1.89 \times 10^{-10}$	16.21	16.8	9.9		$1.12 \times 10^{-10}$
	19	18.9	636	7.75	35.1	3.3		$1.55 \times 10^{-10}$	17.52	18.5	5.5		$1.09 \times 10^{-10}$
	25	25.1	612	7.05	48.2	15.7		$1.31 \times 10^{-10}$	15.52	26.4	13.6		$7.44 \times 10^{-11}$
	40	38.3	626	7.03	27.8	2.1		$2.25 \times 10^{-10}$	14.21	20.2	10.7		$9.21 \times 10^{-11}$
Melamine faced board (particle board)	16	15.5	700	7.80	146.3	20.4	8932	$3.88 \times 10^{-11}$	10.52	162.8	22.2	11 270	$1.05 \times 10^{-11}$
	25	25.3	631	7.33	111.8	18.3	8117	$5.50 \times 10^{-11}$	10.77	120.2	9.6	11 925	$1.55 \times 10^{-11}$
	40	38.6	635	7.46	57.9	14.5	5854	$1.05 \times 10^{-10}$	10.41	78.0	14.7	11 162	$2.37 \times 10^{-11}$
Substrate of laminate flooring (particle board)	7	6.6	799	7.58	94.8	3.1		$4.90 \times 10^{-11}$	15.95	38.4	3.3		$3.99 \times 10^{-11}$
Laminate flooring (particle board)	7	6.8	840	8.34	200.5	5.4	3689	$2.11 \times 10^{-11}$	13.24	149.8	18.7	3862	$1.01 \times 10^{-11}$
MDF (V20)	3	2.9	856	8.01	58.9	3.6		$7.41 \times 10^{-11}$	11.88	31.1	8.5		$4.55 \times 10^{-11}$
	6	6.0	848	6.73	42.4	4.1		$1.25 \times 10^{-10}$	12.15	27.1	7.5		$4.71 \times 10^{-11}$
	10	9.9	811	6.61	39.0	4.0		$1.39 \times 10^{-10}$	14.70	24.8	1.0		$5.51 \times 10^{-11}$
	16	16.7	726	6.98	20.4	6.5		$2.78 \times 10^{-10}$	14.11	13.4	5.8		$1.17 \times 10^{-10}$
	19	18.9	810	6.69	33.4	4.3		$1.62 \times 10^{-10}$	12.82	22.9	1.6		$5.87 \times 10^{-11}$
	25	25.0	749	6.57	20.4	1.3		$2.83 \times 10^{-10}$	12.91	15.4	1.8		$9.49 \times 10^{-11}$
Melamine faced board (MDF)	40	40.2	766	6.04	16.6	7.1		$3.69 \times 10^{-10}$	11.29	13.9	6.2		$9.64 \times 10^{-11}$
	16	16.0	779	6.36	132.8	30.5	8900	$4.52 \times 10^{-11}$	9.03	145.9	5.0	10 556	$9.39 \times 10^{-12}$
	25	24.4	783	6.81	120.4	5.3	12 085	$4.47 \times 10^{-11}$	8.73	155.4	16.0	17 059	$9.03 \times 10^{-12}$
Substrate of laminate flooring (HDF)	7	6.4	876	6.49	54.5	13.6		$9.36 \times 10^{-11}$	12.81	36.7	3.6		$3.31 \times 10^{-11}$
Laminate flooring (HDF)	7	6.5	925	6.73	289.0	5.1	5060	$1.62 \times 10^{-11}$	9.50	251.3	4.4	4656	$4.59 \times 10^{-12}$
	8	7.6	953	6.47	349.8	11.9	7525	$1.33 \times 10^{-11}$	10.95	207.6	18.1	4397	$5.52 \times 10^{-12}$
MDF wall panel	15	14.9	536	7.76	13.5	1.3		$5.21 \times 10^{-10}$	12.51	8.9	2.0		$2.44 \times 10^{-10}$

boards, the coefficients of variation are much higher due to the irregularity of the span size (OSB) and of the bonding (plywood, coated boards).

Under dry conditions, the water vapour resistance factor is up to two times higher than under wet conditions (except for laminate flooring). The diffusion coefficient is also higher under dry than under wet conditions although the opposite was expected. Wu and Suchsland (1996) also measured decreasing diffusion coefficients with increasing moisture content for particle board. They interpret this observation as follows: the dominant moisture transfer mechanism in particle and fibre boards is water vapour diffusion through air-filled pore spaces, while bound wa-

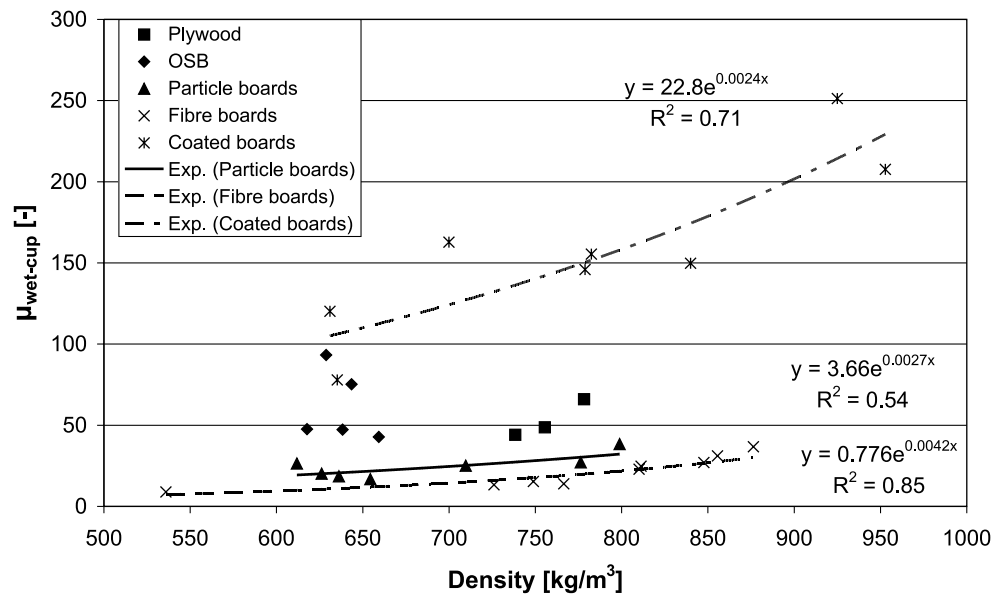
ter diffusion, such as in solid wood, is less pronounced. According to Ganev et al. (2003), who analysed MDF, the increase or decrease of the diffusion coefficient with increasing moisture content depends on the sorption direction of the measurements. The diffusion coefficient decreases with increasing moisture content in adsorption and increases with increasing moisture content in desorption.

For the uncoated fibre and particle boards and the coated boards, a clear density influence is obvious for both the water vapour resistance factor and the diffusion coefficient (Figs. 3–6). While in both differential climates (dry cup and wet cup) the water vapour resistance factor rises exponen-



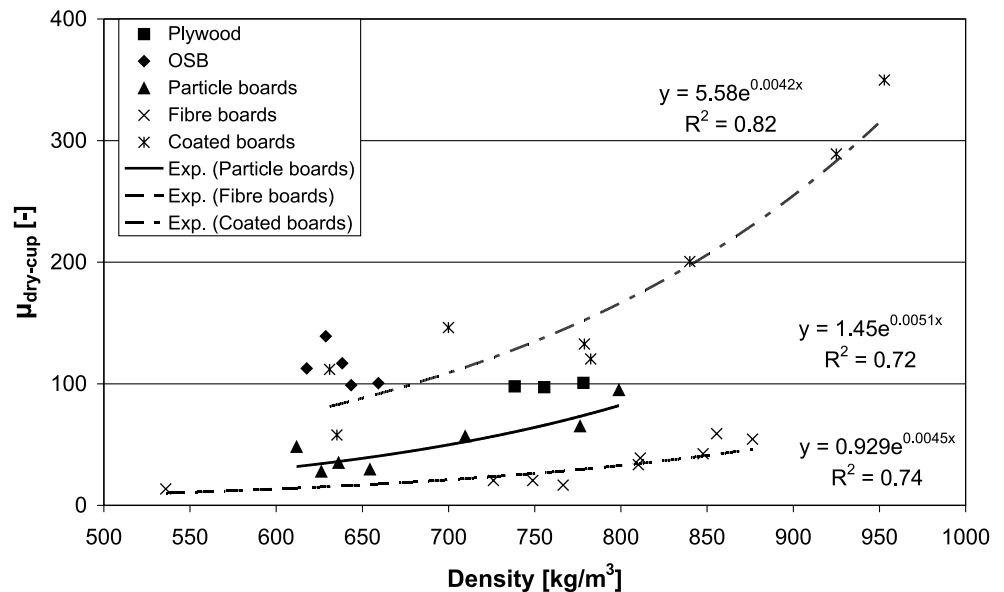
**Fig. 3** Water vapour resistance factor ( $\mu$ ) of the wet cup tests depending on the density (mean values)

**Abb. 3** Wasserdampfdiffusionswiderstandszahlen ( $\mu$ ) im Feuchtbereich (wet cup) in Abhängigkeit von der Dichte (Mittelwerte)



**Fig. 4** Water vapour resistance factor ( $\mu$ ) of the dry cup tests depending on the density (mean values)

**Abb. 4** Wasserdampfdiffusionswiderstandszahlen ( $\mu$ ) im Trockenbereich (dry cup) in Abhängigkeit von der Dichte (Mittelwerte)



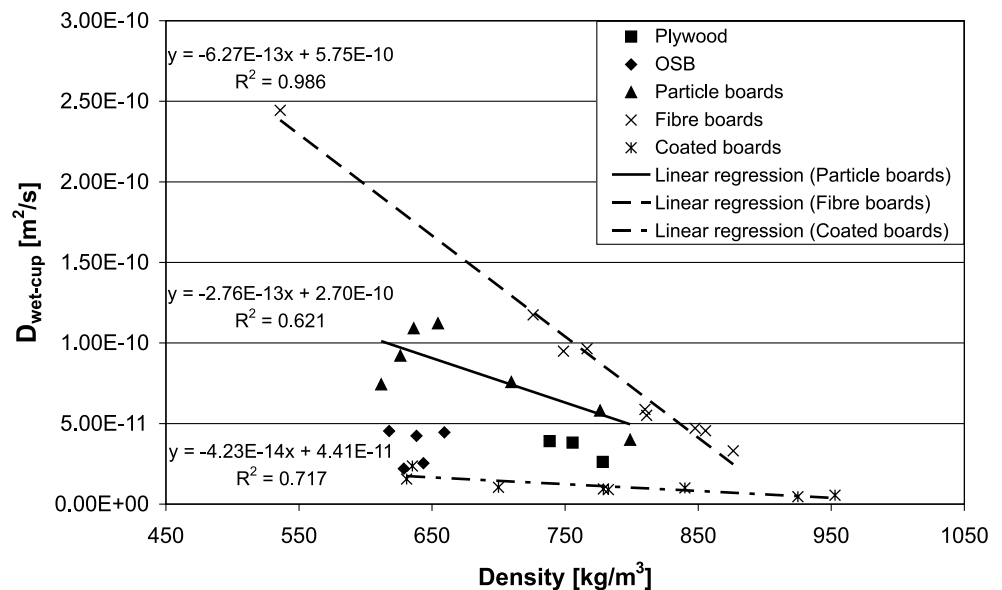
tially with increasing density, the diffusion coefficient linearly declines.

Furthermore, a slight influence of the board thickness was found for the water vapour resistance factor of particle and fibre boards, but this interferes with the influence of the density (Table 3). The influence of the thickness possibly results from the different density profiles perpendicular to the plate and the coating, respectively. To evaluate this in detail, Drewes (in Kiessl and Möller 1989) has evaluated the influence of the density profile for urea and phenolic resin-bonded raw particle boards. He found that the face layers had a 4- to 10-fold higher water vapour resistance factor than the middle layers. This ratio, however, declines with increasing moisture content.

The water vapour resistance factor of the melamine faces strongly varies: the lowest values were found for laminate flooring with a substrate of particle board, the highest values were measured for melamine faced MDF (Table 3). Various factors influence these results, such as different structures of the faces (melamine or phenolic faces, thicknesses of 0.1 or 0.2 mm), equilibrium moisture content (EMC), thickness and density of the board, and others. The values of the wet cup tests are mostly higher than those of the dry cup tests. Presumably, the used apparent EMC (not more than 0.1% change of weight within 24 h) differs more from the true EMC for wet cup tests (higher differences of moisture content) than for dry cup tests resulting in too high water vapour resistance factors.

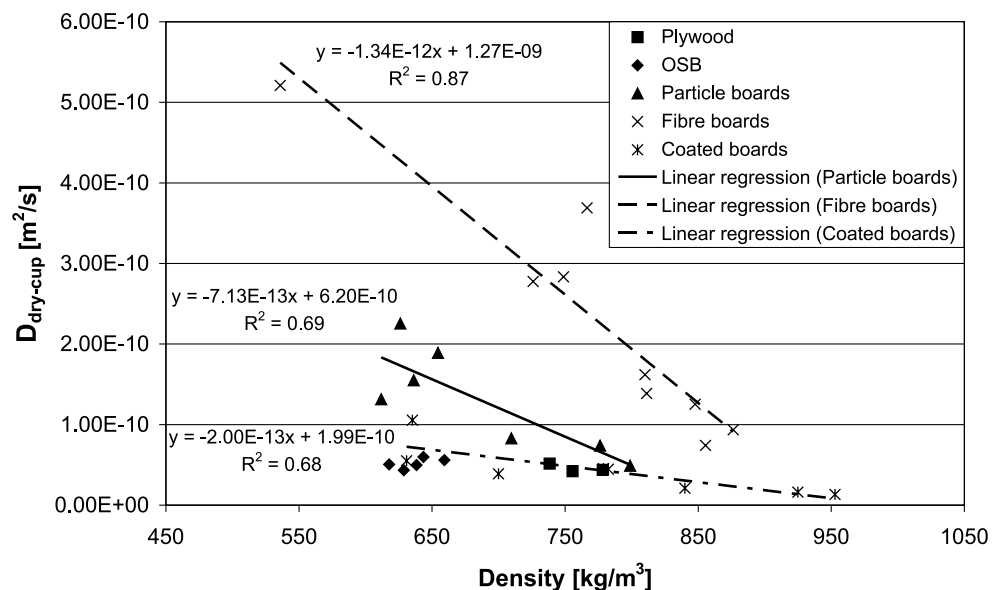
**Fig. 5** Diffusion coefficients ( $D$ ) of the wet cup tests depending on the density (mean values)

**Abb. 5** Diffusionskoeffizienten ( $D$ ) im Feuchtbereich (wet cup) in Abhängigkeit von der Dichte (Mittelwerte)



**Fig. 6** Diffusion coefficients ( $D$ ) of the dry cup tests depending on the density (mean values)

**Abb. 6** Diffusionskoeffizienten ( $D$ ) im Trockenbereich (dry cup) in Abhängigkeit von der Dichte (Mittelwerte)



## Conclusion

Various dependencies between the thermal conductivity and the water vapour resistance as well as density, moisture content, temperature, board thickness and particle size were determined for the investigated wood-based materials. Thermal conductivity increases with rising temperature, moisture content and density but the slope of the increase depends on the wood-based material. The comparison of different materials with a similar density level resulted in a clear reduction of the thermal conductivity with decreasing particle size, but no influence of the board thickness was found. The water vapour resistance factor increases with rising density and decreases with increasing moisture

content. In contrast, the diffusion coefficient decreases with rising density and moisture content. Furthermore, for uncoated particle and fibre boards as well as coated materials, the water vapour resistance decreases with increasing board thickness.

## References

- Bader H, Niemz P, Sonderegger W (2007) Untersuchungen zum Einfluss des Plattenbaus auf ausgewählte Eigenschaften von Massivholzplatten. Holz Roh- Werkst 65(3):173–181
- Cammerer JS (1956) Bezeichnungen und Berechnungsverfahren für Diffusionsvorgänge im Bauwesen. Kältetechnik 8(11):339–343



- Cammerer J, Achtziger J (1984) Einfluss des Feuchtegehaltes auf die Wärmeleitfähigkeit von Bau- und Dämmstoffen. Bauforschungsbericht des Bundesministers für Raumordnung, Bauwesen und Städtebau, Bonn, F 1988. IRB Verlag, Stuttgart
- Ganev S, Cloutier A, Beauregard R, Gendron G (2003) Effect of panel moisture content and density on moisture movement in MDF. *Wood Fiber Sci* 35(1):68–82
- ISO 12572 (2001) Hygrothermal performance of building materials and products – Determination of water vapour transmission properties. Geneva
- ISO 8302 (1991) Thermal insulation – Determination of steady-state thermal resistance and related properties – Guarded hot plate apparatus. Geneva
- Kiessl K, Möller U (1989) Zur Berechnung des Feuchteverhaltens von Bauteilen aus Holz und Holzwerkstoffen. Selektion feuchtetechnischer Stoffeigenschaften. *Holz Roh- Werkst* 47(8):317–322
- Kollmann F (1951) Technologie des Holzes und der Holzwerkstoffe. Anatomie und Pathologie, Chemie, Physik, Elastizität und Festigkeit, Bd. 1, 2. Aufl. Springer, Berlin Göttingen Heidelberg
- Niemz P (1993) Physik des Holzes und der Holzwerkstoffe. DRW-Verlag, Leinfelden-Echterdingen
- Radovic B, Cheret P, Heim F (2001) Konstruktive Holzwerkstoffe. Holzbau Handbuch, Reihe 4, Teil 4, Folge 1 (2. Aufl.). Arbeitsgemeinschaft Holz eV, Düsseldorf
- Siau JF (1995) Wood: Influence of moisture on physical properties. Department of Wood Science and Forest Products, Virginia Polytechnic Institute and State University, Keene, NY
- Schneider A, Engelhardt F (1977) Vergleichende Untersuchungen über die Wärmeleitfähigkeit von Holzspan- und Rindenplatten. *Holz Roh- Werkst* 35(7):273–278
- Sonderegger W, Niemz P (2006) Untersuchungen zur Quellung und Wärmedehnung von Faser-, Span- und Sperrholzplatten. *Holz Roh- Werkst* 64(1):11–20
- Suleiman BM, Larfeldt J, Leckner B, Gustavsson M (1999) Thermal conductivity and diffusivity of wood. *Wood Sci Technol* 33(6):465–473
- Wu Q, Suchsland O (1996) Prediction of moisture content and moisture gradient of an overlaid particleboard. *Wood Fiber Sci* 28(2):227–239